Foundational Training on Semiconductor Fabrication and Characterization

Project Presentation on
wide bandgap Semiconductors :GaN, Sic and their Processing Challenges.

जनजातीय कार्य मंत्रालय
MINISTRY OF
TRIBAL AFFAIRS

CeNSE

Project Presentation on
Wide bandgap Semiconductors: GaN, Sic and their Processing Challenges.

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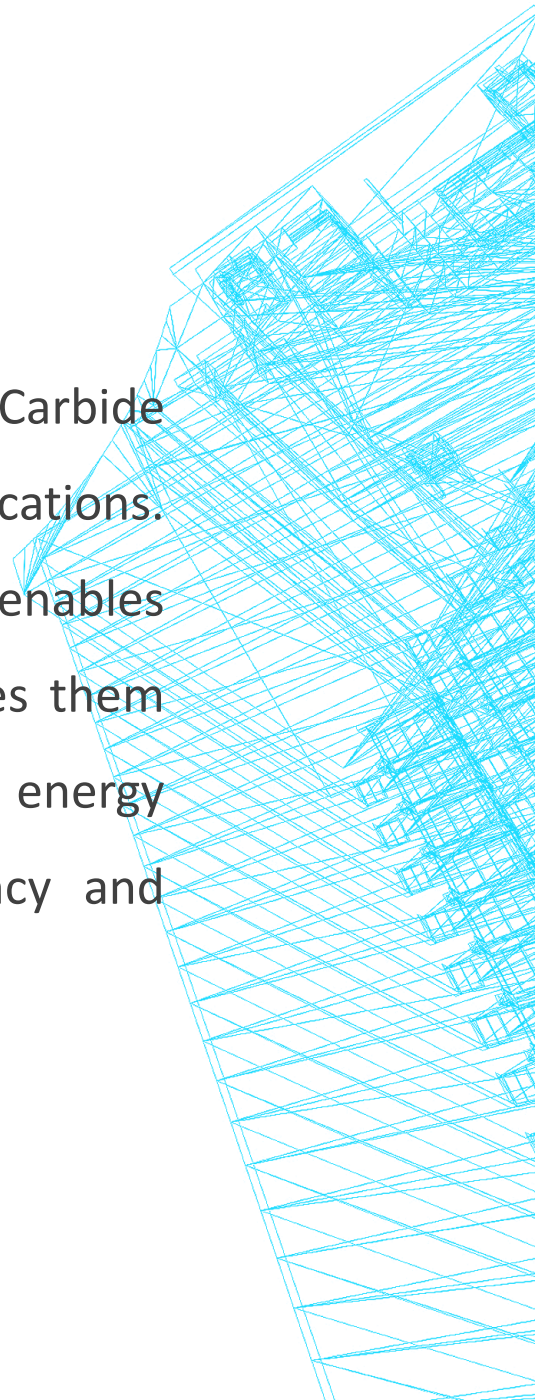
1. Introduction

Wide Bandgap (WBG) semiconductors such as Gallium Nitride (GaN) and Silicon Carbide (SiC) have emerged as key materials for high-performance power electronic applications. Compared to traditional silicon, these materials possess a larger bandgap, which enables them to operate at higher voltages, temperatures, and frequencies. This makes them particularly suitable for advanced applications like electric vehicles, renewable energy systems, aerospace, and high-frequency communication. Their high efficiency and compact size allow for reduced energy losses and improved system performance.



What are Wide Bandgap Semiconductors?

Wide Bandgap semiconductors are materials that have a bandgap energy typically greater than 2.2 eV. This wide bandgap allows devices to tolerate higher electric fields, leading to higher breakdown voltages and lower conduction losses

What are Wide Bandgap Semiconductors?

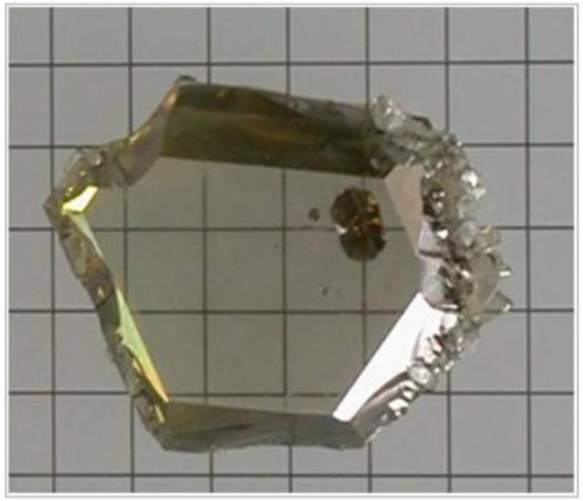
Gallium Nitride GaN

GaN (3.4 eV) is a direct bandgap semiconductor known for high-speed switching and efficiency, making it ideal for RF amplifiers, power supplies, and fast chargers. It is often used in HEMTs for low to medium voltage applications. However, it must be grown on foreign substrates like silicon or sapphire, which poses processing challenges.

Silicon Carbide (SiC)

SiC (3.3 eV) is a wide bandgap semiconductor with high thermal conductivity and breakdown voltage, ideal for high-voltage, high-temperature uses like EV inverters and industrial drives. It is grown on native SiC substrates for better quality but is expensive to manufacture due to its hardness and brittleness.

A. Silicon



B. Gallium Nitride Crystal

A. Silicon Carbide

Figure: These are the three basic semiconductor materials currently serving the high-voltage applications.

Source: Bonnie Baker

Advantages Over Silicon

Performance Benefits of Wide Bandgap Semiconductors

High Breakdown Voltage

GaN and SiC devices sustain much higher voltages than silicon counterparts, exceeding 1.2 kV.

Superior Thermal Conductivity

Enhanced heat dissipation allows higher power densities and reliability.

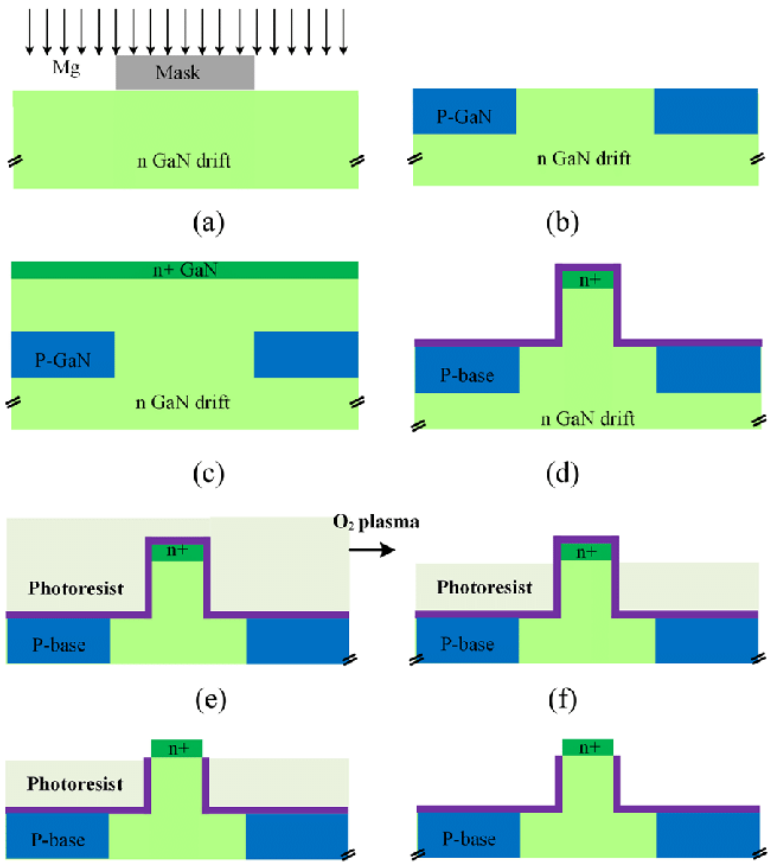
Faster Switching Speeds

Lower losses and higher efficiency in high-frequency applications.

Fabrication Steps Overview

GaN Device Processing

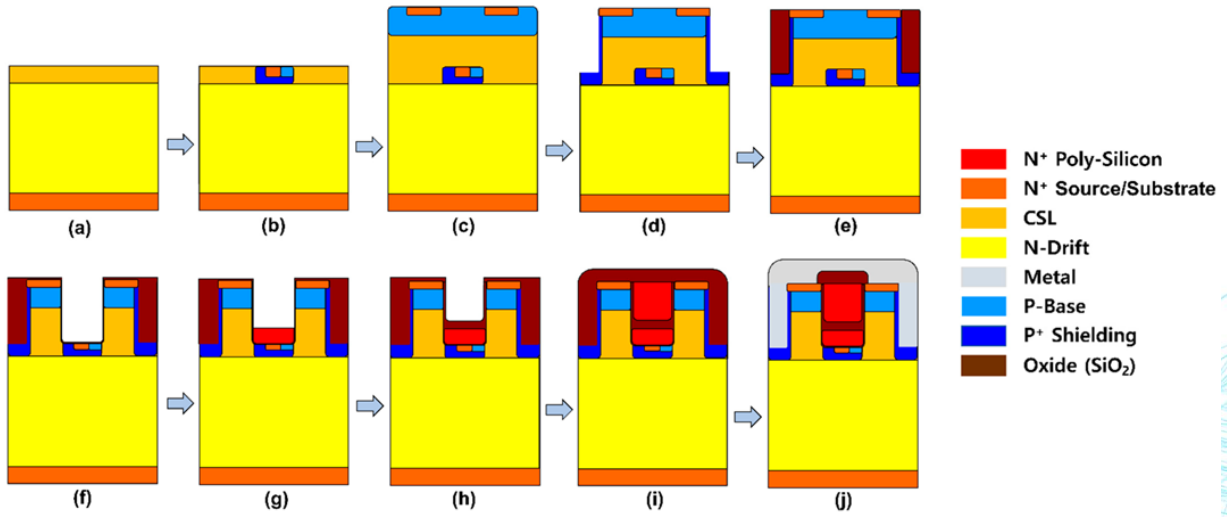
1. Substrate Preparation
2. Mg Implantation
3. P-GaN Etching
4. n+ GaN Deposition
5. Photolithography
6. O2 Plasma Etching
7. Photoresist Removal
8. Final Structure



Fabrication Steps Overview

SiC Device Processing

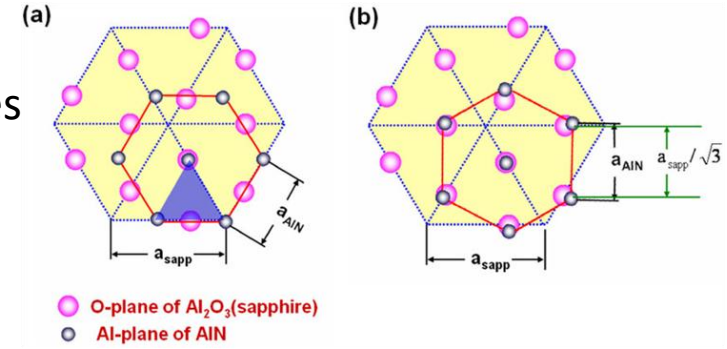
1. Substrate Preparation
2. N+ Poly-Silicon Deposition
3. CSL Formation
4. N-Drift Layer Growth
5. P-Base Implantation
6. P+ Shielding Addition
7. Metal Contact Formation
8. Oxide (SiO2) Deposition
9. N+ Source/Substrate Etching
10. Final Metallization



Substrate Issues and Material Challenges

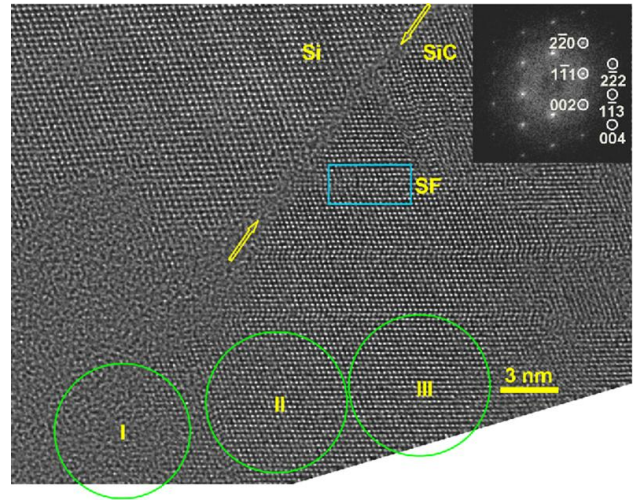
GaN

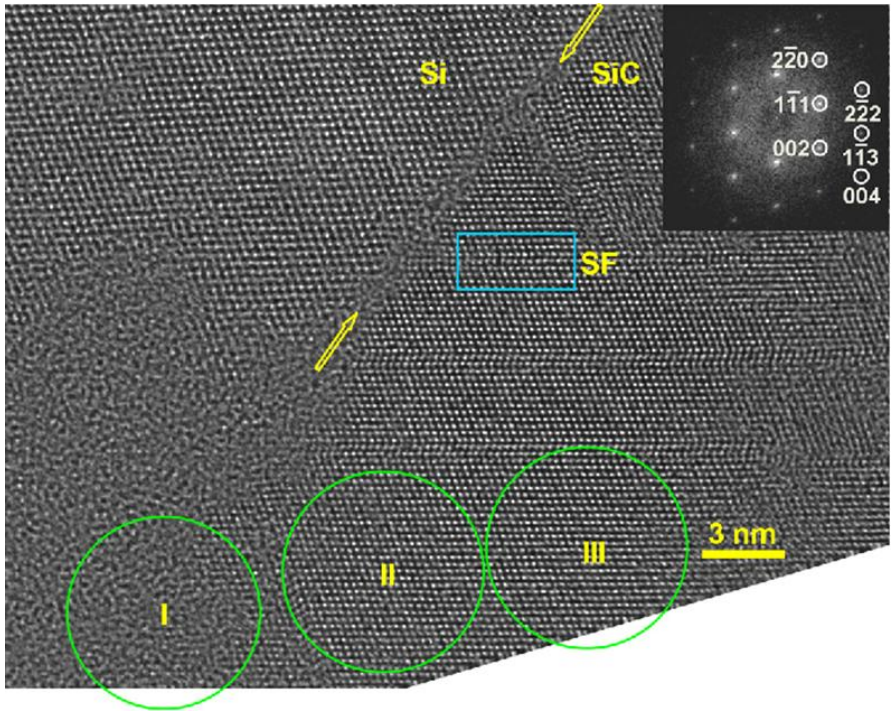
- **Lattice Mismatch with Substrates**: Mismatch with Si or sapphire causes strain, impacting device quality.
- **High Defect Density on Si**: Defects in GaN-on-Si reduce yield and performance.
- **Wafer Bowing and Cracking**: Stress from growth processes can deform or crack wafers.



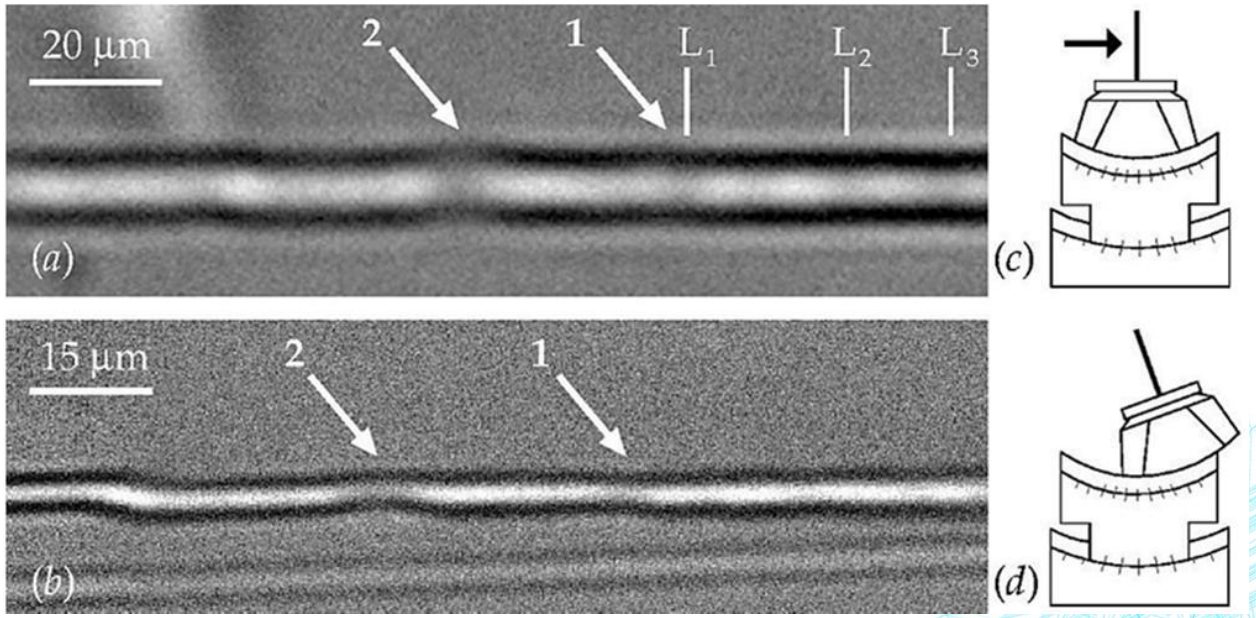
SiC

- **Expensive High-Quality Bulk Wafers**: High-purity SiC wafers are costly, limiting scalability.
- **Micropipe Defects**: Crystal imperfections degrade device reliability and performance.
- **Limited Wafer Size (Improving)**: Smaller wafers restrict production scale, though 150mm+ sizes are emerging.





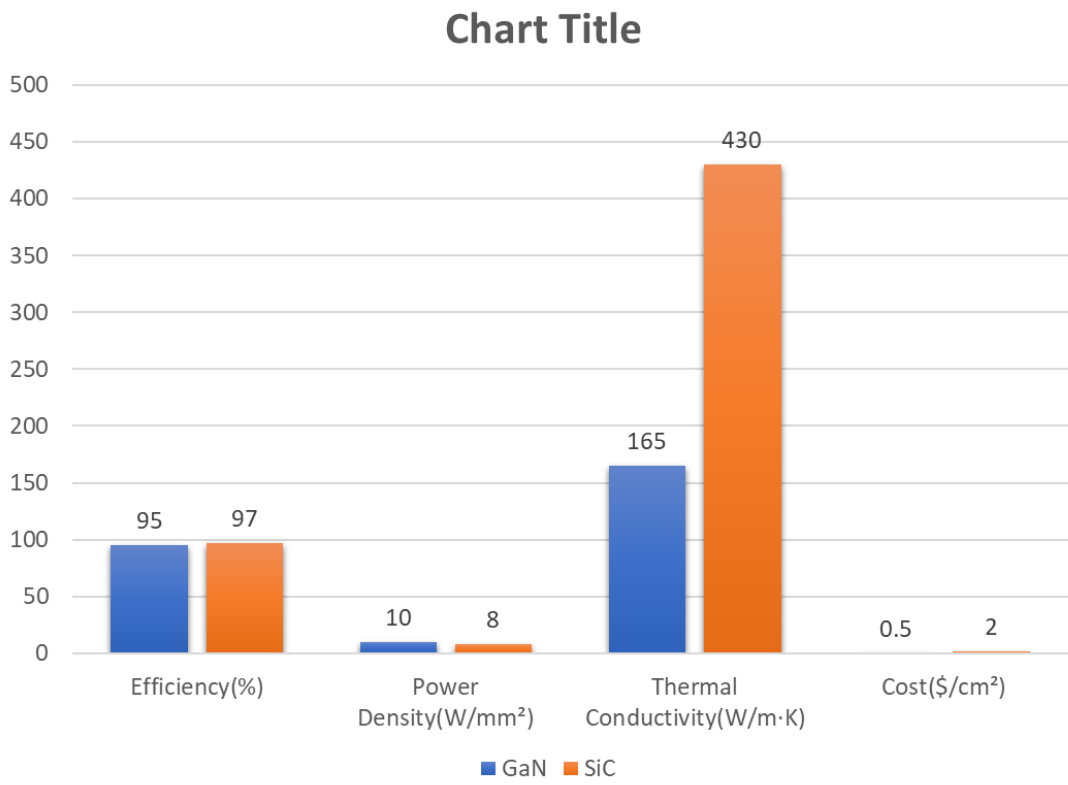
Si defect microscopy



SiC micropipe image

Device Performance Comparison

Parameters	Gan	Sic
Efficiency	High at low voltages (~95%)	Excels at high voltages (~97%)
Power density	~10 W/mm² (compact)	~8 W/mm² (robust)
Thermal conductivity	~130-200 W/m·K	~370-490 W/m·K
Cost	Lower (GaN-on-Si: ~$0.5/cm²)	Higher (~$2/cm²)



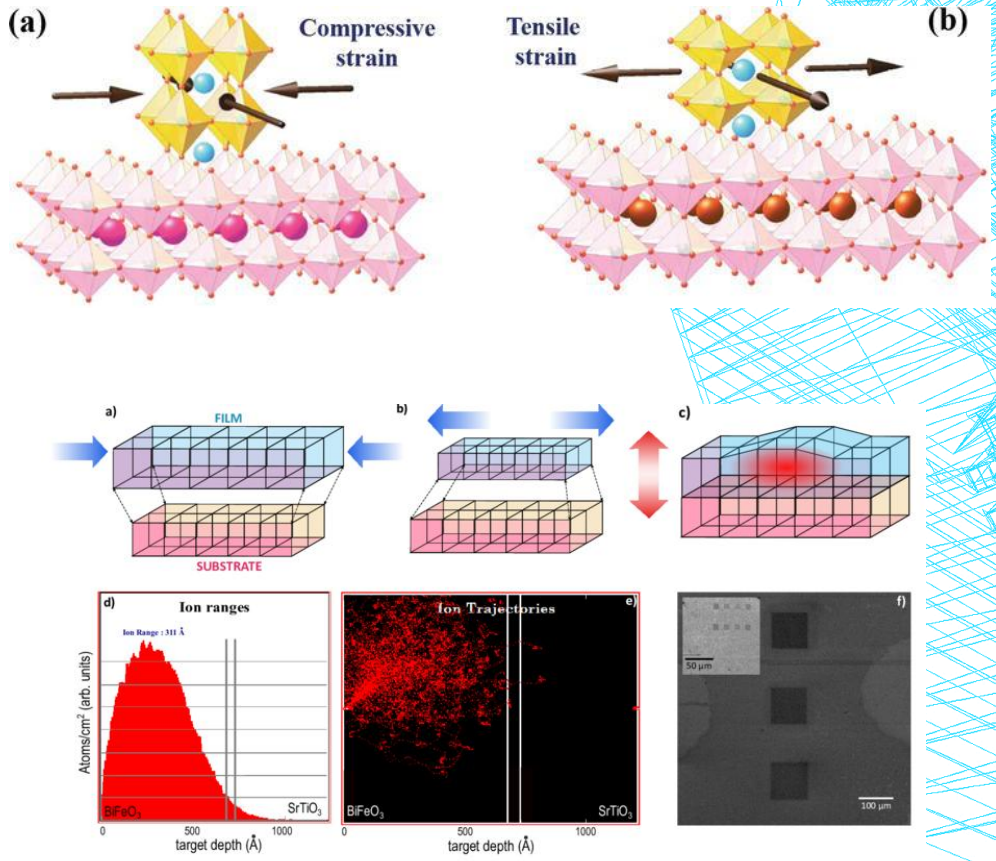
Processing Challenges in GaN

Epitaxy

- **Strain and Dislocations**: Lattice mismatch causes strain, leading to crystal dislocations and reduced reliability.
- **Complex Nucleation Layers**: Specialized layers needed to initiate GaN growth on mismatched substrates.

Contacts

- **Forming Low-Resistance Ohmic Contacts**: Achieving low resistance is critical for efficient power transfer but challenging.



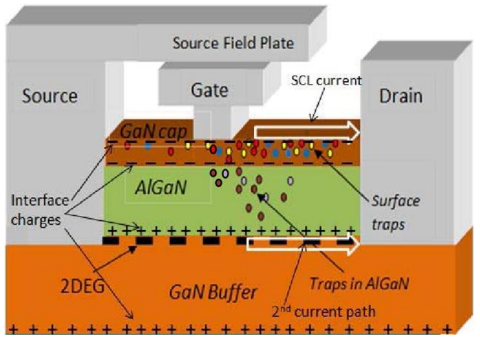
Processing Challenges in GaN

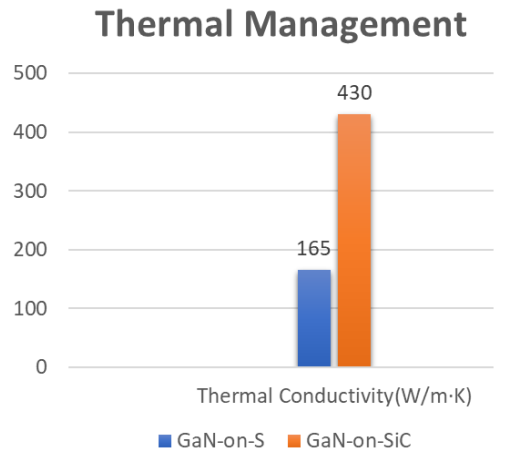
Gate Dielectrics

- Limited Native Oxides: GaN lacks a stable native oxide, complicating insulation.
- Interface Traps Affecting Reliability: Traps at dielectric interfaces reduce device lifespan and performance.

Thermal Management

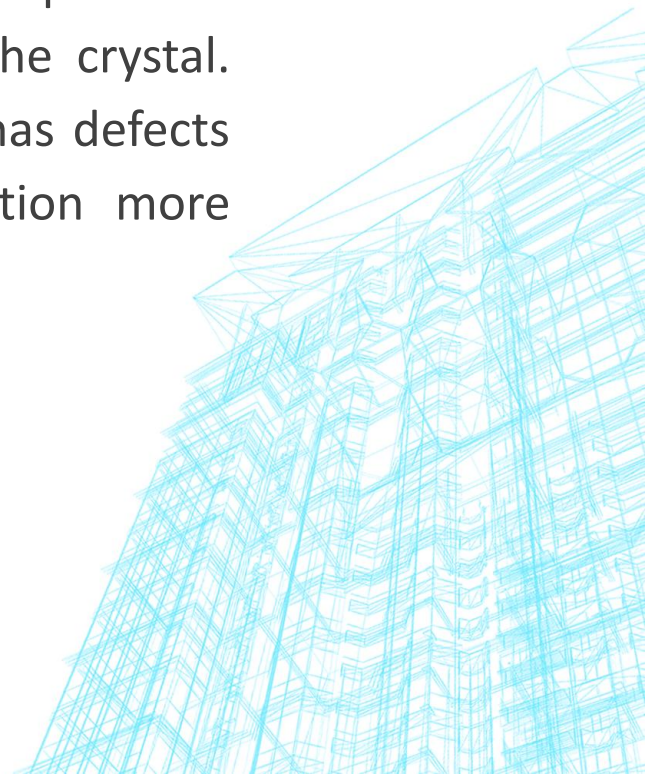
- GaN-on-Si vs. GaN-on-SiC Trade-offs: Si substrates are cost-effective but have poorer thermal conductivity than SiC.





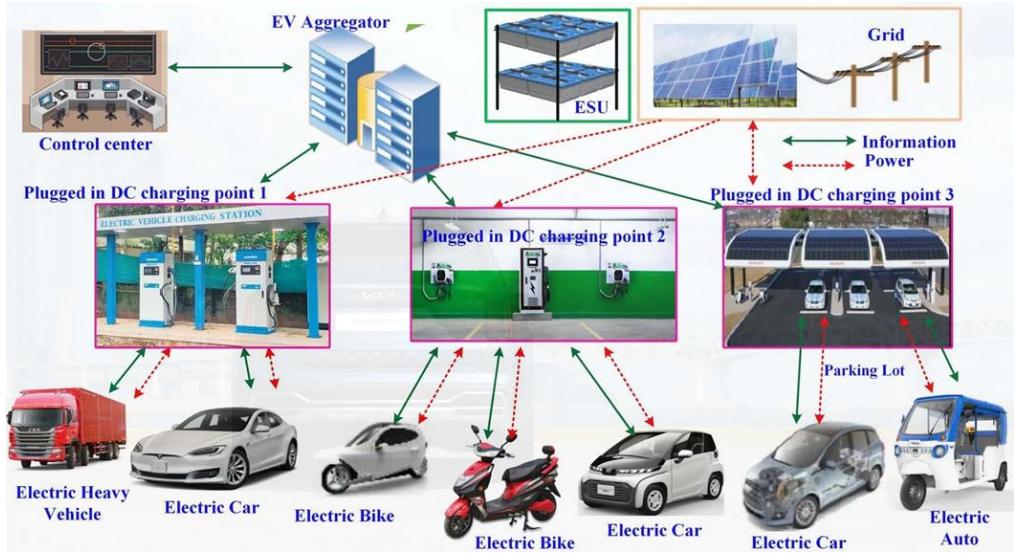
Processing Challenges in SiC

Silicon Carbide (SiC) processing is challenging due to its hardness, making wafer cutting and polishing difficult and costly. Growing defect-free SiC substrates is complex, with common defects like micropipes and dislocations. Doping requires high-temperature annealing above 1500°C to activate implanted ions, which can damage the crystal. Forming a good gate oxide is also difficult, as the SiC-SiO_2 interface often has defects that affect device performance. These factors make SiC device fabrication more expensive and technically demanding than silicon.



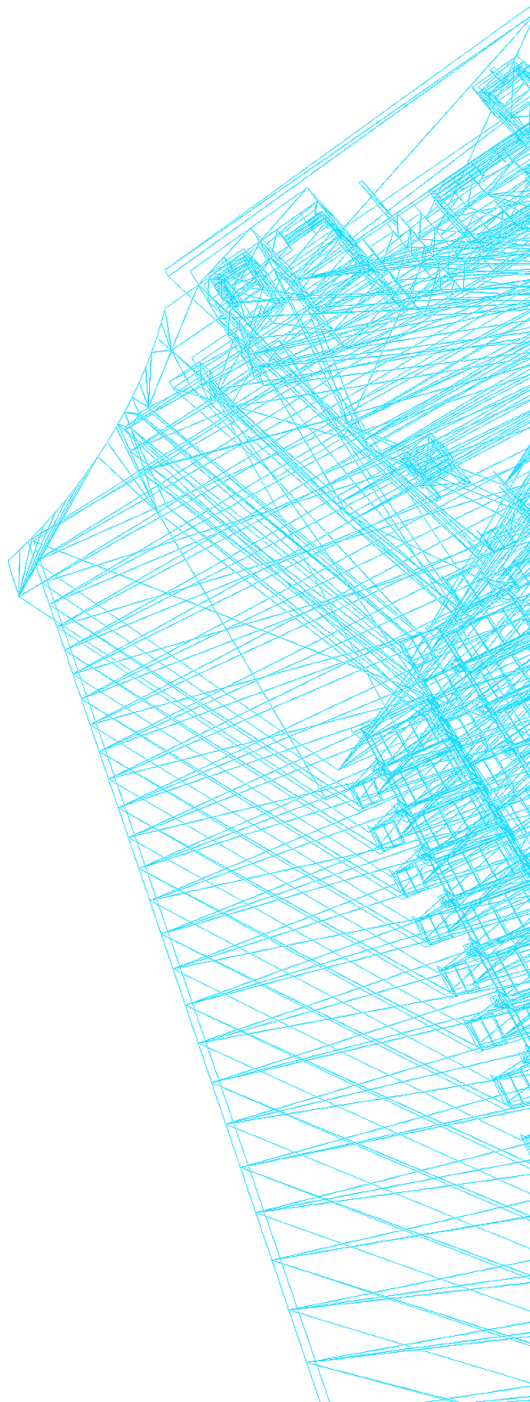
Applications in Power Electronics

- Electric Vehicles: GaN and SiC enable compact, efficient powertrains, improving range and charging speed for EVs.
- Renewable Energy Inverters: High-efficiency GaN/SiC inverters maximize energy harvest from solar and wind systems.
- Server Power Supplies: GaN-based supplies offer high power density, reducing data centre energy costs and space.



Applications in Power Electronics

- RF Amplifiers: GaN’s high-frequency capabilities enhance performance in 5G and radar applications.
- Industrial Motor Drives: SiC’s robustness ensures reliable, high-power control for heavy-duty industrial motors.

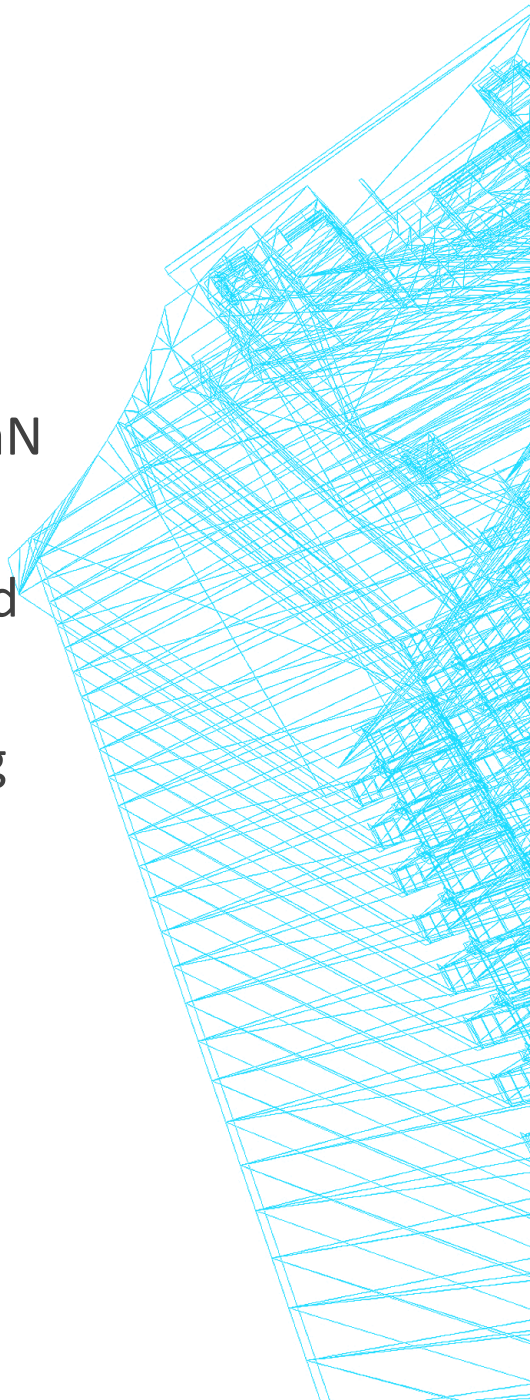


GaN vs SiC Comparison

While both materials are considered superior to silicon, they serve different roles based on their strengths. GaN is preferred in applications where high switching speed and compact design are required, especially below 1200 V. SiC is better suited for applications above 1200 V, where thermal performance and voltage handling are more critical. GaN is typically grown on silicon, making it more cost-effective, while SiC offers better substrate quality but at a higher price. Ultimately, both materials complement each other in the next generation of power electronics.

Recent Developments

Recent technological advancements have improved the viability of both GaN and SiC in commercial markets. GaN-on-Si integration has become more efficient, reducing costs for consumer-level devices like phone chargers and power adapters. Vertical GaN transistors are being developed to improve current handling and scalability. On the SiC side, manufacturers are moving toward larger wafers (200 mm), which helps reduce the cost per device. Additionally, hybrid modules combining SiC and GaN are being explored to leverage the strengths of both materials in a single system.



Conclusion

In conclusion, GaN and SiC are transforming the field of power electronics with their wide bandgap properties that enable high efficiency, high voltage, and compact system design. Although both materials face fabrication and substrate-related challenges, the performance benefits they offer are unmatched by traditional silicon technology. As research continues to advance, the adoption of these materials is expected to accelerate across industries, enabling smarter, faster, and more energy-efficient power systems for the future.

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